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DEVELOPMENT AND INVESTIGATION OF PROTECTIVE PROPERTIES OF THE ELECTROMAGNETIC AND SOUNDPROOFING SCREEN

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Розроблено технологію виготовлення універсального електромагнітного та шумозахисного екрана на основі пінолатексу та пінополістиролу. Проведені дослідження дисперсності та фізичних характеристик компонентів матеріалу для екранування електромагнітного поля та шуму. Розроблений матеріал складається з латексу та залізорудного пилу з переважною дисперсністю 12 мкм. Для підвищення шумозахисних властивостей у процесі виготовлення латексу до нього додавався піноутворювач – синтетична олеїнова кислота. Для зменшення ваги у матеріал додавався гранульований полістерол розмірами 1–3 мм. Проведені дослідження екранів товщинами 5 мм та 10 мм з різним вмістом металевої субстанції. Визначено, що коефіцієнти екранування матеріалу товщиною 5 мм для вмісту залізної руди 5–20 % складають: для електромагнітного поля частотою 2,4–2,6 ГГц – 1,8–44; для магнітного поля промислової частоти – 1,2–15,0. Для матеріалу товщиною 10 мм – 2,9–52,0 та 2,3–38,4 відповідно. Індекс зниження шуму 41–44 дБ досягається на частотах шуму 6–8 кГц, найбільш критичних для людини. Проведені структурні дослідження поверхні матеріалів. Встановлено, що за вмісту металевої субстанції від 15 % її розподіл у тілі матеріалу стає нерівномірним. Для підвищення ефективності електромагнітного захисту доцільно попередньо виготовити із залізорудного пилу магнітну або реологічну рідину і використати її у технологічному процесі виготовлення пінолатексу. Доведено, що комбіновані електромагнітні та шумозахисні (акустичні) екрани, маючи малу товщину та вагу, можуть забезпечити зниження рівнів електромагнітних полів та шуму до нормативних, що особливо важливо при їх застосуванні у транспортній галузі

Ключові слова: електромагнітний екран, шумозахисний екран, залізорудний пил, коефіцієнт екранування, пінолатекс, пінополістирол

1. Introduction

A stable current trend is the increased electromagnetic and acoustic load on production and household environment, as well as the environment in general. This is predetermined by an increase in the number, and the denser arrangement, of electrical and electronic equipment at industrial and residential facilities, by the development of in-house networks of wireless communication, electric power supply grids, by the more intensive transportation flow, etc. In recent years, there have been stricter requirements to vehicles as the sources of electromagnetic fields and noise. However, reducing the levels of these physical factors in the aviation, railroad, and automobile transport through screening is very complicated. It was established experimentally that the restricted properties of protective materials in civil aviation promote the lowering of noise levels, but this does not apply to the levels of electromagnetic fields. However, it is the level of electromagnetic fields that affects not only people, but the stability in operation of electronic equipment as well. In addition, crew members must comply with the highest demands regarding the condition of their health. Under conditions of confined spaces, it is problematic to simultaneously install multiple means of protection against the acoustic and electromagnetic loads.

That relates to the critical importance of dimensions and weight of protection means at transportation vehicles. Under such circumstances, it is a relevant task to develop and implement combined electromagnetic and soundproofing (acoustic) screens, which, given their small thickness and weight, would make it possible to reduce the levels of electromagnetic fields and noise to match the norms.

2. Literature review and problem statement

Designing and studying protective screens have been paid much attention to. However, development of technologies for electromagnetic and acoustic screens is a separate direction. The field of materials fabrication for protection against electromagnetic fields has two areas – the screens to reduce the levels of fields of ultra-low frequencies and those to reduce the levels of electromagnetic radiation at very high and highest frequencies. Low-frequency screens are made mostly of metals. Study [1] proposed a lattice screen to normalize the magnetic fields from electric power lines. Such a screen is effective only for the quasi-stationary field of industrial frequency and must have large dimensions. For the higher frequencies, dimensions of the grid cells should match a single wave length. Such screens are suitable for blocking a monochrome radiation. Most continuous electromagnetic screens are composite. However, they have specific purposes. For example, paper [2] suggested a screen to reduce the levels of electromagnetic fields from personal computers. Computers have the defined range of frequencies in the generated electromagnetic field, which has strict constraints in terms of amplitude (integral value). Thus, such a screen is not applicable for other purposes. That is also true for an electromagnetic screen to absorb the electromagnetic radiation of mobile phones [3].

Research over the past years has shown that the effectiveness of shielding improves with an increase in the dispersion of metallic particles in a composite material [4]. This screen is based on the nanosized iron in the form of a magnetic fluid. The cost of magnetic fluid is very high, which is why it is impractical to use it to fabricate screening surfaces of large areas.

The possibilities of making shielding surfaces from nanocomposites based on carbon were investigated in [5]. However, the fabrication technology of such materials is very complicated, hence its price is high. In this case, small thicknesses (2–3 mm) do not provide for proper efficiency (shielding factor is (1.1–1.3.) The most acceptable is the electromagnetic screen based on iron ore dust and latex [6]. Its advantage is in a wide range of shielding an electromagnetic field. Its effectiveness, however, crucially depends on the size of metallic particles, while the body of the screen (a polymeric matrix) is quite thick to absorb mechanical waves (lack of porosity).

The situation is similar in the field of development of soundproofing (acoustic) screens). Most of the screens to protect against aircraft noise and noise of automobile transport are the thin hard surfaces whose efficiency is predetermined by the diffraction phenomena at the edges of the screens [7]. The efficiency of a screen, based on the physical properties of a material, was partly considered in [8]. The work gives estimation; theoretical results are not always in good agreement with field measurements.

A perforated screen is used in order to mute sound [9]. Given its closed shape, it reduces the sound level from a source and does not interfere with ventilation. However, if such a screen is used for the simultaneous reduction of the levels of an electromagnetic field, it would prove effective starting from the defined minimum wavelength. The most acceptable, in terms of performance, are the multi-layered acoustic screens (so-called "sandwich systems") [10]. The parameters for the individual layers of a material can be adjusted based on the wave resistance so that the screen could be most effective for the specified amplitude-frequency characteristics of an acoustic field. One of the layers could be used for the simultaneous screening of an electromagnetic field, but this complicates the design. Such materials have great thickness and specific weight. Moreover, there are problems related to the adhesion of layers in multilayered structures during operation.

The available literary sources revealed only several developments concerning the simultaneous protection of people against electromagnetic fields and noise (for example, patent USA US7141974B2), relating to magnetic-resonance tomographers [11]. This is due to the fact that such research refers to defense.

Thus, the task that has remained unsolved up to now is to develop and study the protective properties of universal electromagnetic and acoustic screens with a maximally isotropic structure. Such materials should possess small thickness and weight, and their application must be acceptable in the transportation sector.

3. The aim and objectives of the study

The aim of this work is to design a complex electromagnetic and soundproofing screen, which would be effective in the most common frequency ranges of electromagnetic and acoustic fields, at small thickness and weight.

To accomplish the aim, the following tasks have been set:

– to explore the dispersity and physical characteristics of components, and to develop a technology to fabricate a metallic-polymeric material that would shield the electromagnetic field and noise;

– to investigate the protective properties of the material regarding a reduction in the levels of magnetic fields at the most common frequencies;

– to examine the noise-protection characteristics of the material taking into consideration the reduced levels of noise at octave frequency bands;

– to define the basis for streamlining the process of designing the screens based on experimental and calculation methods, providing for a graphical-analytical representation on the selection of parameters for a screen with the required protective properties. To study the material structurally and to suggest possible ways for its improvement.

4. Methods and procedures to study the protective properties of an electromagnetic and soundproofing screen

This study was performed using the method of direct measurement of the magnetic field intensity, energy flux density of the electromagnetic field, and the level of noise.

We measured the intensity of magnetic field at industrial frequency by the verified tension meter of electric and magnetic field at industrial frequency PZ-50 according to the manual. The maximum basic measurement error did not exceed 20 %. Given the quasi-stationarity of the magnetic field of industrial frequency, the screen used for testing was geometrically closed. It was of a cylindrical shape with an outer diameter of 200 mm with wall thickness of 5 and 10 mm. The shape was chosen due to the existence, for a cylinder, of a mathematical apparatus for the estimated determination of screen efficiency. The ends of the cylinder had caps made of the same material. The measuring antenna was placed in the middle of the screen and was connected to the measuring device with a cable. When measuring the intensity of the magnetic field of industrial frequency, the outer background levels of the magnetic field of industrial frequency did not exceed 0.02 μT.

The availability of experimental data about a shielding factor, as well as the corresponding mathematical apparatus, enables determining the effective magnetic permeability of a material. This parameter allows the further design of protective screens with required properties, based on the actual electromagnetic environment.

In order to determine the shielding factors for electromagnetic radiation at ultra-high frequency, we employed the calibrated meter of energy flux density PZ-31, in line with the manual. The maximum basic measurement error did not exceed 2.7 dB.

In order to determine shielding factors, we fabricated flat-panel screens the size of 0.75x0.75 m, which fit into a slot in a metallic sheet, non-transparent to radiation. Dimensions of the sheet ensured the absence of radiation penetration beyond the screen. The measuring antenna was located in the geometric center of the screen, which overlapped radiation from the source. The background of the outer electromagnetic radiation did not exceed 0.08–0.10 μW/cm^2 (in the range of 3–30 GHz), which made the application of an anechoic chamber optional. In order to measure the protective properties of the material, we used a test signal at frequencies of 2.4–2.6 GHz, which are the most common frequencies under industrial and household conditions. Shielding implies a reduction in the field in a protected area both through reflection and absorption of electromagnetic waves.

For a magnetic field of ultra-high frequency, a shielding factor is the ratio between the intensities of a magnetic field in front of and behind the screen.

For electromagnetic radiation of ultra-high frequency, a shielding factor is the ratio between the respective energy flows densities.

The soundproofing properties of the material were determined at the reverberation chamber of acoustic laboratory at the National Aviation University (Kyiv, Ukraine). The condenser microphones and stationary calibrated equipment made by Brüel&Kjær (Denmark) were employed for the measurements.

In accordance with the ISO 140 standards, soundproofing is determined using two sound-measuring chambers; it is calculated from ratio:

$$R = 10\lg\frac{W_1}{W_2}, \qquad (1)$$

where W_1, W_2 are, accordingly, the sound power in the chambers of high and low levels, W. Provided that the acoustic field in sound-measuring chambers is diffuse, ratio (1) is recorded in the following form:

$$R = L_1 - L_2 + 10\lg\frac{S}{Q}, \qquad (2)$$

where L_1, L_2 are, respectively, the levels of sound pressure (SPL) in the chambers of high level (HLC) and low level (LLC), dB; S is the area of the examined surface of the panel, installed between the flanges of sound-measuring chambers, m^2; Q is the equivalent sound absorption area in LLC, m^2. If sound damping is neglected, the equivalent sound absorption area is then determined from the following formula in the ISO 354:2003 standard:

$$Q = \frac{55{,}3V}{cT_p}, \qquad (3)$$

where V is the volume of LLC, m^3; $c = 20{,}1\sqrt{T}$ is the speed of sound in air, m/s; T is the absolute temperature of air, K; T_p is the reverberation time in LLC, s. In line with the standard method for determining a panel soundproofing, the equivalent sound absorption area (3) is calculated using the ratio provided by the ISO 16283-1:2014 standard:

$$Q = \frac{0{,}16V}{T_p}. \qquad (4)$$

The time of reverberation (the period over which a sound pressure level (SPL) is reduced by 60 dB) in the low pressure chamber was determined experimentally. Error of measurement of the sound pressure level is not more than 2 dB. The indicator of soundproofing efficiency of a screen is the index of noise reduction, that is, the difference between the levels of noise in front of and behind the screen. Sound waves of different frequencies damp in different ways (at low frequency – slower, at high frequency – faster). Therefore, determining the effectiveness of soundproofing is performed in the octave frequency bands in line with ISO 140-4-1998.

In order to determine the distribution of the metallic and metal-containing substances in a polymer (matrix), we used the metallographic microscope MIM-8 (VTP "ASMA-PRYLAD", Ukraine).

In order to determine the dispersion of the substance that enables the shielding of electromagnetic fields, we conducted a granulometric analysis applying a sedimentation method employing the torsional scale.

5. Starting materials and a technology for the fabrication of universal electromagnetic and soundproofing screens

We have chosen latex as the base.

To enable the simultaneous shielding of an electromagnetic field and the mechanical (sound) waves, a material must have the following appropriate properties: to absorb electromagnetic energy, to reflect electromagnetic waves, and to demonstrate acceptable values for basic mechanical characteristics. These characteristics include: the Young modulus (E), 11 GPa; a shear modulus (G), 4.1 GPa; the Poisson ratio within the range of 0.44; density, 1,470–1,530 kg/m^3. When comparing such a material with known analogs used in civil aviation, for example, the material Twintex, the Young modulus is 15.7 GPa, the shear module is 6.3 GPa, the Poisson ratio is 0.204, density is 1,430 kg/m^3; this indicates that the mechanical properties of latex are satisfactory.

The technology for the production of latex is well-known and established. The advantage of latex is that, as shown in [6], in the process of its fabrication, it is possible to add a finely-disperse metallic and a metal-containing substance to it in the amount of up to 20 %; the polymer does not lose its mechanical properties. In order to obtain the required shielding factors, the starting components, during latex manufacturing, were supplemented with iron-ore dust in the required amount (by weight) and with the desired dispersion. The dispersion of iron-ore dust depends on the place of extraction and the enrichment of ore, so this indicator was investigated in advance. Appropriate data will be given in the next chapter.

Our choice of the iron-ore dust as a filler for the polymeric matrix was predetermined by the following considerations. Iron-ore dust was selected from the dust-absorbing screens in an aspiration system at the iron ore crushing station. This predetermines the high enough dispersion of the material and large percentages of iron and its compounds in the products of ore enrichment. Depending on the location of dust selection, the amount of materials that ensure the shielding of electromagnetic fields is: Fe – 43.3–57.5 %; FeO – 7.6–14.8 %; Fe_3O_4 – 4.3–6.8 % (data provided by Novokrivoryzky Ore Dressing Plant, Ukraine).

In order to provide for the high soundproofing properties, a material must be structurally heterogeneous. That is why latex with added iron-ore dust is produced in the form of foam-latex. To this end, prior to the thermal treatment of the starting mixture, we added a foam-forming agent (synthetic oleic acid) in the amount of 1.1–1.7 %. Thickness of the fabricated samples was 5–1 mm.

In order to enhance the structural heterogeneity of the material, we also produced a series of samples with the addition of the finished granulated foam-polystyrene. A granule fraction was 1 to 3 mm. The resulting thickness of the obtained sheet materials at the end of the technological cycle was 5 and 10 mm.

The protective properties of an electromagnetic composite screen (shielding factor) are largely dependent on the dispersity of a metallic and a metal-containing substance. Therefore, in order to determine this parameter, we performed a granulometric analysis of the starting iron-ore dust.

When designing electromagnetic screens, of importance are the indicator of distribution of shielding particles and the determination of a domination fraction. To this end, we analyzed a dependence of the number of particles in iron-ore dust dQ/drQ_{max} on size r in the total mass of the material (Fig. 1). Particles without iron content were not taken into consideration; they were washed out in aqueous solution in the process of sedimentation.

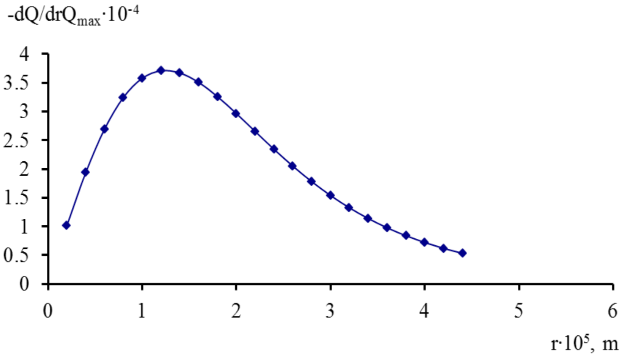


Fig. 1. Distribution of the relative quantity of iron-ore dust particles ($-dQ/drQ_{max}$) based on their size (r)

Fig. 1 shows that the dominating fraction of the utilized iron-ore dust is formed by particles the size of 12 μm and close to them. The resulting distribution of particles based on size is required for the further development and production of electromagnetic screens on the principles of reasonable sufficiency, that is, providing for a guaranteed reduction of the intensity of a magnetic field and the energy flux density to the levels that are lower than those maximally permissible. The overall shielding factors and coefficients of electromagnetic wave reflection depend on the dispersion of metallic impurities [6].

6. Results of studying the protective properties of electromagnetic and soundproofing screens

We studied the protective properties of electromagnetic screens made from foam-latex in the region of ultra-high frequencies at radiation frequencies of 2.4–2.6 GHz. The frequency of 2.4 GHz is the radiation frequency used in the wi-fi wireless communication; that of 2.45 GHz – in microwave devices whose application does not require licensing; that of 2.6 GHz – in mobile communication of the standard 3G.

We examined a series of screens with a thickness of 5 mm and 10 mm with a different content of the metallic substance. The results of measuring the shielding factors (K_s) depending on the content (by weight) of the shielding substance (ρ, %) are given in Table 1.

Table 1

Dependence of shielding factors for electromagnetic fields at ultra-high frequencies on thickness of the screen and content of the metallic substance

ρ, %	K_s	
	5 mm	10 mm
5	1.8	2.9
10	10.2	18.7
15	33.0	38.0
20	44.0	52.0

Similar tests were performed for the magnetic field of industrial frequency (Table 2).

Table 2

Dependence of shielding factors for the magnetic field of industrial frequency on thickness of the screen and content of the metallic substance

ρ, %	K_s	
	5 mm	10 mm
5	1.2	2.3
10	4.7	10.8
15	11.0	24.0
20	15.0	38.4

The content of a metallic substance in a polymeric matrix (ρ) in the range of 5–20 % was chosen for the following reasons: Tables 1 and 2 show that the shielding factors for materials with such concentrations of iron-ore dust are rather high. The practice of monitoring the electromagnetic environment at enterprises that are the most saturated with sources of electromagnetic fields such as turbogenerator halls at power plants, electrical workshops, civil aviation aerodromes, rolling stock of electric transport, reveals that the levels of magnetic and electromagnetic fields almost never exceed the maximally permissible levels by 3–4 times. Therefore, the effectiveness of the examined electromagnetic screens could prove excessive, even for tasks on ensuring the electromagnetic compatibility between electrical and electronic equipment. In addition, an increase in the concentration of metallic impurities would result in deterioration of the mechanical properties of screens, which could complicate their installation under actual conditions.

We measured shielding factors for the material containing iron-ore dust in the amount of 10 %, as well as the granulated foam-polystyrene (a content of 30 % by volume).

The shielding factors for the frequency of an electromagnetic field with frequencies of 2.4–2.6 GHz were 5.2–5.8; for the magnetic field of industrial frequency 50 Hz – 2.2–2.3.

In order to estimate a shielding factor for the cylindrical screen, we performed a numerical calculation of a two-dimensional magnetic field applying the finite element method employing the software package Comsol. The estimated region with the indicated finite element grid is shown in Fig. 2. Because of the relatively large length of the cylindrical screen, it is assumed that the magnetic field does not depend on the longitudinal coordinate *z*; we investigated the distribution of this field in the region of the $x0y$ cross-section. In addition, given the existing symmetry, we shall consider the field only in region $x>0$.

The distribution of a magnetic field in such a system is described by the following differential equation for a vector magnetic potential, which includes a single *z*-component:

$$\nabla\times\left(\frac{1}{\mu_0\mu_r}\nabla\times A\right)=0, \tag{5}$$

where μ_0 is the magnetic permeability of vacuum, and μ_r is the relative permeability of the medium, which is equal to 1 for an air region and accepts different values in the range of 1÷1,000 for the screen region. Boundary values for the field problem under consideration are shown in Fig. 2. B_0 is the external homogeneous magnetic field whose value is assumed known.

The results of calculation of the magnetic field induction in the region protected by the screen area (marked by a semi-circle) at different values for the magnetic permeability of the screen and its thickness of 10 mm are shown in Fig. 3; the values, obtained based on these data, for shielding factor K_s, as a function of the shielding screen permeability and its thickness are shown in Fig. 4.

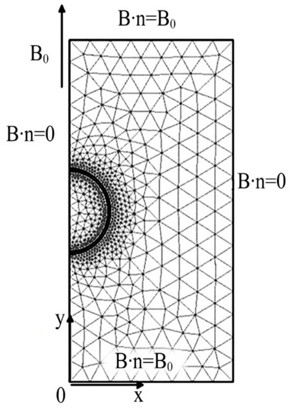


Fig. 2. Region for the calculation of a magnetic field of the cylindrical screen with the indicated finite element grid

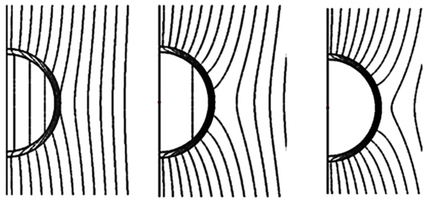

μ_r=10 μ_r=100 μ_r=1000

Fig. 3. Distribution of force lines of the magnetic field at different values of magnetic permeability for the cylindrical screen

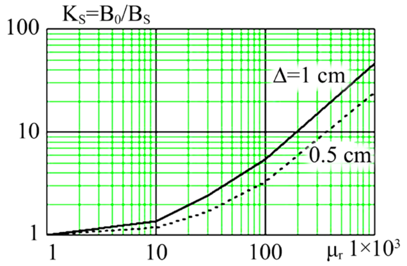


Fig. 4. Dependence of the magnetic field shielding factor on magnetic permeability of the screen at its different thickness

We tested the soundproofing properties of the foam-latex screen with a thickness of 10 mm, and the foam-latex screen with foam-polystyrene with a thickness of 5 mm. These properties are defined by the index of noise reduction (dB), which depends on the frequency of sound waves.

Fig. 5 shows that the continuous registration of the noise reduction index does not provide enough information on the soundproofing properties of the material, but testifies to the complexity of their dependence on the frequency of sound. According to the ISO 140-4-1998 standard, as well as the national standard of Ukraine, the levels of noise at the octave frequency bands are normed based on the different maximally permissible values. This is explained by the varying sensitivity of the human ear to different frequencies.

The results of measurement of reduction in the noise levels at octave frequency bands are shown in Fig. 6.

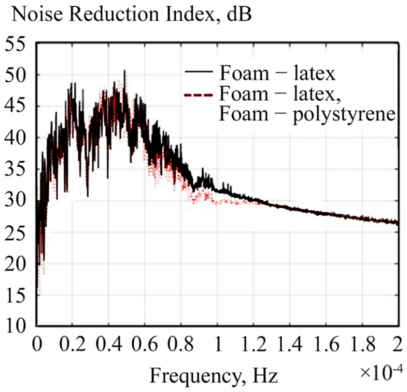


Fig. 5. Dependence of a decrease in the level of noise on frequency of the sound waves of screens made from foam-latex, and from foam-latex with foam-polystyrene granules

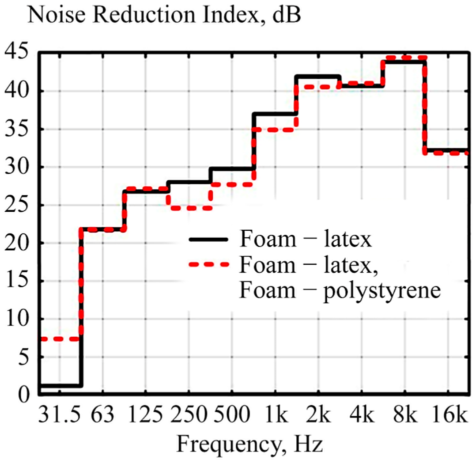


Fig. 6. Reducing the levels of noise by soundproofing screens made from foam-latex and from foam-latex with foam-polystyrene granules

Based on the results of our study, it was found that the effectiveness of a soundproofing screen increases with an increase in the frequency of sound waves. In this case, the largest indexes of noise reduction are at frequencies of 6–8 kHz, to which the human ear is most sensitive, while the maximally permissible noise levels are the toughest. Determining a reduction in the level of noise in the protected region by the reflection of sound waves, at least for application in the transportation sector, has almost no practical importance. This is predetermined by the fact that the sources of noise levels that exceed the norm are outside vehicles and areas of people concentration.

Consideration of a possibility to influence the overall shielding factor for the reflection of a magnetic field with ultra-low (industrial) frequency also does not make much sense.

However, significant coefficients of reflection of electromagnetic radiation with ultra-high frequency under actual industrial conditions could become critical in the presence of internal sources of radiation. It is possible that there is an increase in the electromagnetic background through the repeated reflection of external radiation from shielding surfaces, for instance at equipment facilities at enterprises of civil aviation. In addition to the impact on people, this can affect the stability of operation of electronic equipment (electromagnetic compatibility). In order to determine a possibility of avoiding the effect of such radiation on staff, we investigated reflection coefficients K_r for the obtained composite material depending on the content of a metallic substance ρ in line with a procedure given in [6] (Table 3).

Table 3

Dependence of reflection coefficients of electromagnetic fields of ultra-high frequencies on the content of a metallic substance

ρ, %	5	10	15	20
K_r	0.06	0.11	0.28	0.32

The above data indicate that the reflection coefficients of a metallic-polymeric material containing the iron-ore filler are much lower than those for metallic protective screens. That allows us to conclude that the major contributor to the shielding factor for a material is the absorption of electromagnetic energy.

7. Discussion of results of studying the protective properties of universal electromagnetic and soundproofing screens

The results of the research considered above demonstrate that it is possible to construct a universal electromagnetic and soundproofing screen for the simultaneous reduction in the levels of electromagnetic fields and noise.

It is expedient to analyze the efficiency of application of screens made from foam-latex and from foam-latex and foam-polystyrene. The granules of foam-polystyrene, given their low density compared to foam-latex, are actually the voids in the body of the base material. That contributes to the absorption of sound waves in accordance with known physical laws. Even though the sample with granules is twice thinner than the sample made from solid foam-latex, its noise protection properties almost do not differ (variation is by 2–3 dB). Such a deviation can be considered negligible. Thus, for a band of sound waves of 4–8 kHz, a decrease in the noise levels in both cases is 41–44 dB. The maximum levels of noise at enterprises in energy generation and machine plants at marine vessels are 90–110 dB. That is, the application of the developed screens reduces noises much below the maximally permissible values for these enterprises (80 dB). In many cases, under such conditions, it is necessary to decrease the levels of magnetic fields (turbogenerator plants, vessel generators). It is known that the levels of magnetic fields near such equipment could be higher by 1.5–1.8 times. That is, even the use of screens containing granulated foam-polystyrene can normalize the levels of these fields in a manufacturing space. And the application of continuous foam-latex is possible at smaller thicknesses of the material. It is advisable to streamline the screen design process. The most difficult task is determining the effective magnetic permeability of a material to estimate the required thickness of a screen. With the experimental data regarding the shielding of a magnetic field of industrial frequency for a cylindrical solid screen, it becomes possible to precisely calculate the value for effective magnetic permeability μ [6]:

$$K_s = \frac{\mu(b^2 - a^2)}{4b^2}. \quad (6)$$

where K_s is the shielding factor; a is the inner radius of the cylindrical magnetic screen; b is the outer radius of the cylindrical magnetic screen.

Knowing this parameter enables unique identification of parameters for a screen of required efficiency.

Experimental data indicate a dramatic increase in shielding factor K_s and a significant increase in effective magnetic permeability μ_r at concentrations of iron-ore dust greater than 10 %. This fact requires a reasonable interpretation. To this end, we measured a change in specific electrical conductivity σ of a material depending on the content of iron-ore dust ρ. Determining the material's specific conductivity involved the measurement of an inverse magnitude, specific resistance, using the method of a double bridge. Research results are shown in Fig. 7.

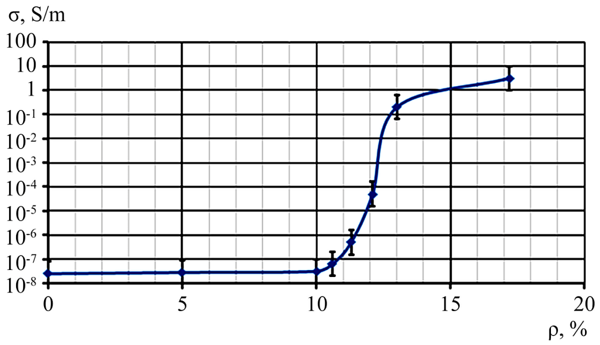


Fig. 7. Dependence of specific conductivity σ of the metallic-polymeric screen on the content of iron-ore dust ρ

The specified data indicate that a significant increase in electrical conductivity occurs at the content of iron-ore dust about 10.5–11 %. That is, a growth in the material's shielding factor happens at the threshold of the flow of electric current. This agrees well with the provisions of continuum media electrodynamics and is important in order to design screens. An increase in the material's specific electrical conductivity leads to an increase in the reflection coefficient of electromagnetic waves, which in many cases is undesirable.

When designing a screen, it is necessary to considered actual operating conditions, which will make it possible to define a balance between values for the total shielding factor and reflection coefficient of electromagnetic waves.

High indices of noise reduction are predetermined by the porosity of the material and the presence of foam-polystyrene granules. In this case, in the presence of structural inhomogeneities (granules' pores), a given material is essentially isotropic, with a regular arrangement of inhomogeneities. This has advantages in comparison with known solutions, multi-layered structures, in terms of both efficiency and thickness, manufacturability and cost.

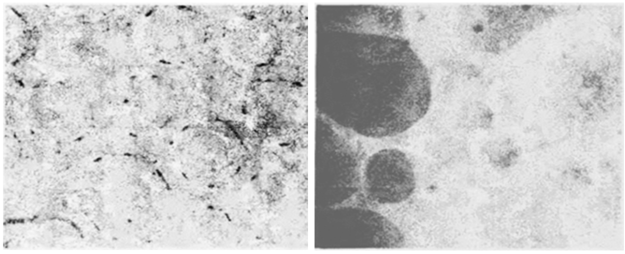
In order to ensure the effectiveness of shielding electromagnetic and acoustic fields, the areas of screens should be large, which is why using latex and iron-ore dust brings down the means of protection. In comparison with the analogues, screens based on a magnetic fluid applying nano-iron [4], the developed protective material is much cheaper and comparable in terms of efficiency. At the same time, the iron dust is disposed of.

Difficulties of using iron-ore dust for the manufacture of protective materials refer to the difference in characteristics of iron ore at different deposits and enterprises, and its enrichment stations. Thus, at the previous stages of the development and production of screens, it is necessary to determine the chemical composition and dispersion of the chosen iron dust.

It is advisable to identify ways for improving the developed shielding material, which would make it possible to further reduce its thickness and weight.

In order to control acoustic characteristics of a material, it would be appropriate to alter the amount of a foam-forming agent in the production of foam-latex, which changes the size of pores, as well as modify the fraction size and concentration of foam-polystyrene granules.

We performed a structural study into the cut sections of foam-polystyrene at different content of iron-ore dust (Fig. 8).



a *b*

Fig. 8. Structure of the material's cut surface at different content of iron-ore dust: *a* – 10 %; *b* – 15 % (×40)

The above structures indicate that at the content of a shielding substance of 15 % there appear some inhomogeneities in the material (Fig. 8, *b*).

To improve it, there should be techniques to enhance the uniformity of distribution of shielding particles in the polymer. Such a technique could involve a preliminary preparation, on the base of iron-ore dust, of a magnetic or a rheological fluid, which could be used in the technological process for manufacturing protective materials.

In order to prepare such fluids in the form of colloidal solutions, it is necessary to apply surface-active substances, which prevent the clumping of particles. However, in this case, there may occur problems related to the adhesion of particles in foam-latex. Nevertheless, this direction seems promising and thus requires further research.

8. Conclusions

1. A granulometric analysis of iron-ore dust using the method of sedimentation of this iron-ore dust has revealed that the dominant fraction is the particles of about 12 μm. This is acceptable to use it as a filler in a composite metallic-polymeric protective material. To ensure the soundproofing properties, a standard technological process of the manufacture of latex was supplemented with a foam-forming agent (synthetic oleic acid). That increased the porosity and soundproofing properties of the material. In order to reduce the thickness of the material without compromising its soundproofing properties, the granulated foam-polystyrene was added to it, whose granules' diameters were 1–3 mm.

2. The test of the developed materials to reduce the levels of electromagnetic fields has shown that at frequencies 2.4–2.6 GHz at the content of iron-ore dust of 10 % (by weight) the polymeric matrix exhibits a sharp increase in shielding factor, from 10.2 (10 %) to 44.0 (20 %). The shielding factor almost linearly increases with the increase in the thickness of the screen. In the presence of evenly distributed granulated foam-polystyrene in foam-latex (30 % by volume) the shielding factor of the electromagnetic field reduces two-

fold. The shielding factors for the magnetic field of industrial frequency monotonically ascend from 1.2 to 15.0 with the increase in the content of the metallic substance from 5 to 20 % (thickness is 5 mm). When adding foam-polystyrene, this indicator reduces by two times. Increasing the thickness of the screen improves the shielding factor almost linearly as well.

3. The study of the screens soundproofing properties of has showed that the increase in the index of noise reduction occurs with the increase in the frequency of sound waves. Determining a noise reduction index at octave frequency bands has revealed that its largest values (41–44 dB) are for the frequency of sound waves at 6–8 kHz, the frequency of the highest sensitivity of the human ear. Adding to foam-latex the granulated foam-polystyrene (30 % by volume) improves the noise protection properties of the material. Materials made from foam-latex (10 mm) and from foam-latex with foam-polystyrene (5 mm) demonstrate differences in soundproofing equal to 1–2 dB, which, given the overall noise reduction indices (22–44 dB, depending on frequency), is permissible and could not significantly affect people.

4. Streamlined design of the composite electromagnetic/acoustic screen is achieved through the calculation of protective properties of the screen. Initial data for the assessment are the shielding factors for the screen of cylindrical shape, for which we constructed mathematical ratios. A structural study into the surfaces of materials' cuts has established the possibility to improve efficiency of screens due to the enhanced homogeneity of the material. That becomes possible through the preliminary preparation of a magnetic or a rheological fluid based on iron-ore dust for application in the technological process.

References

1. Grinchenko V. S. Mitigation of three-phase power line magnetic field by grid electromagnetic shield // Tekhnichna Elektrodynamika. 2018. Vol. 2018, Issue 4. P. 29–32. doi: https://doi.org/10.15407/techned2018.04.029
2. An Ultrathin and Broadband Radar Absorber Using Resistive FSS / Li M., Xiao S., Bai Y.-Y., Wang B.-Z. // IEEE Antennas and Wireless Propagation Letters. 2012. Vol. 11. P. 748–751. doi: https://doi.org/10.1109/lawp.2012.2206361
3. Singh J. Computer Generated Energy Effects on Users and Shielding Interference // International Journal of Innovative Research in Computer and Communication Engineering. 2015. Vol. 3, Issue 10. P. 10022–10027.
4. A thin electromagnetic shield of a composite structure made on the basis of a magnetic fluid / Glyva V. A., Podoltsev A. D., Bolibrukh B.V., Radionov A. V. // Tekhnichna Elektrodynamika. 2018. Vol. 2018, Issue 4. P. 14–18. doi: https://doi.org/10.15407/techned2018.04.014
5. Low percolation threshold and electromagnetic shielding effectiveness of nano-structured carbon based ethylene methyl acrylate nanocomposites / Mondal S., Ganguly S., Das P., Khastgir D., Das N. C. // Composites Part B: Engineering. 2017. Vol. 119. P. 41–56. doi: https://doi.org/10.1016/j.compositesb.2017.03.022
6. Design and study of protective properties of electromagnetic screens based on iron ore dust / Glyva V., Podkopaev S., Levchenko L., Karaieva N., Nikolaiev K., Tykhenko O. et. al. // Eastern-European Journal of Enterprise Technologies. 2018. Vol. 1, Issue 5 (95). P. 10–17. doi: https://doi.org/10.15587/1729-4061.2018.123622
7. Castiñeira-Ibañez S., Rubio C., Sánchez-Pérez J. V. Environmental noise control during its transmission phase to protect buildings. Design model for acoustic barriers based on arrays of isolated scatterers // Building and Environment. 2015. Vol. 93. P. 179–185. doi: https://doi.org/10.1016/j.buildenv.2015.07.002
8. Korotchenko M. V., Shevchenko Yu. S. Doslidzhennia efektyvnosti akustychnykh ekraniv na avtomobilnykh dorohakh Ukrainy // Naukovo-vyrobnychyi zhurnal. 2012. Issue 6. P. 40–42.
9. Observation of topological valley transport of sound in sonic crystals / Lu J., Qiu C., Ye L., Fan X., Ke M., Zhang F., Liu Z. // Nature Physics. 2016. Vol. 13, Issue 4. P. 369–374. doi: https://doi.org/10.1038/nphys3999
10. Acoustic response of multilayer with viscoelastic material / Abid M., Abbes M. S., Chazot J. D., Hammemi L., Hamdi M. A., Haddar M. // The International Journal of Acoustics and Vibration. 2012. Vol. 17, Issue 2. doi: https://doi.org/10.20855/ijav.2012.17.2300
11. Active-passive electromagnetic shielding to reduce MRI acoustic noise: Pat. No. US 7,141,974 B2 USA. Int. C. GOI/3/00 / Edelstein W. A., Kidane T. K., Taracilla V. et. al. No. 10/925,691; declareted: 25.08.2004; published: 28.11.2006, Bul. No. 1. URL: https://patents.google.com/patent/US7141974B2/en